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6. AUTHOR(S)

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13. ABSTRACT (Maximum 200 words)

A new three dimensional model of very low frequency wave propagation in the earth-ionosphere waveguide, in the presence of localized and transient disturbances, has been developed. The model is generally applicable to disturbances of different shape and origin, although the application up to now has been to interpret observations of ionospheric disturbances associated with lightning-induced electron precipitation from the magnetosphere. This work constituted the PhD disssertation of Mr. William Poulsen.

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FINAL TECHNICAL REPORT FOR N00014-87-K-0299

Title: Subionospheric VLF/LF Propagation in the Presence of Transient and Localized Perturbations of Nighttime D-region

Expiration Date: Sept. 30, 1990

Principal Investigator: Professor U. S. Inan

This project involved the development of a new three dimensional computer-based model of subionospheric VLF propagation in the presence of localized disturbances of the D-region. A list of publications, talks, and PhD thesis developed under this contract are provided in the attachment. In this report, we briefly summarize the program highlights with reference to the listed papers.

The first year of the three year project was devoted to the development of a three dimensional scattering code based on a formulation first published by *Wait* [1962]. An important milestone in the first year of the project (initiated on 1 October 1987) was the acquisition of the existing two dimensional propagation code, the Long Wave Propagation Capability (LWPC), developed and used by the Naval Ocean Systems Center (NOSC). This NOSC/LWPC code was acquired in July 1988 through courtesy of Dr. J. Ferguson of NOSC.

An initial paper describing the basic aspects of the new three dimensional formulation and its application to special cases involving single dominant waveguide modes was submitted to *JGR* during the second year of the program and was published early in 1990 [*Poulsen et al.*, 1990a].

The integration of the three dimensional scattering model into the propagation code so as to allow the treatment of cases with multiple dominant modes was carried out during the third year of the program, and the first application of the new methodology was reported in the Proceedings of the Ionospheric Effects Symposium (IES) [*Poulsen et al.*, 1990b].

A fundamental assumption adopted in the development of the new three dimensional model was to neglect coupling between waveguide modes within the localized scattering center. This assumption was shown to be fully justified for most types of ionospheric disturbances that are expected to be produced by lightning-induced electron precipitation. However, due to this assumption, the applicability of the new model is limited to disturbances with transverse dimensions of at least a few times the wavelength of the scattered waves. A preliminary calculation of the scattering from very small (~5 km) disturbances indicated that much higher electron precipitation fluxes would be required to produce observed subionospheric VLF amplitude/phase changes [*Bell et al.*, 1990]. The complete generalization of the model so that it can be applicable for the treatment of ionospheric disturbances of arbitrary shape was left as a future objective.

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All aspects of this project was carried as part of (or in connection with) the PhD Dissertation of Mr. W. L. Poulsen. Although the funding for the project terminated on 30 September 1990, the completion of the PhD Thesis and associated research papers were unavoidably delayed beyond that time. Mr. Poulsen has now successfully defended his PhD thesis on 7 January 1991 (see enclosed Abstract) and is currently completing his written dissertation with final submittal and graduation expected in April 1991.

At least two research papers are now being prepared based on the PhD Thesis for submission to *Radio Science* and *Journal of Geophysical Research*. The titles of these papers are provided below. These manuscripts are planned to be completed and submitted to the journals by the end of April 1991.

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LIST OF PUBLICATIONS Supported by N00014-87-K-0299

- 1) Poulsen, W. L., T. F. Bell, and U. S. Inan, Three-dimensional modeling of subionospheric VLF propagation in the presence of localized D-region perturbations associated with lightning, *J. Geophys. Res.*, 95, 2447, 1990a.
- 2) Poulsen, W. L., T. F. Bell, and U. S. Inan, Three-dimensional modeling of subionospheric VLF propagation in the presence of localized D-region perturbations associated with lightning, *Proceedings of the Ionospheric Effects Symposium*, Virginia, 1990b.
- 3) Poulsen, W. L., T. F. Bell, and U. S. Inan, VLF scattering from localized disturbances in the lower ionosphere, *Radio Science*, (to be submitted), March, 1991.
- 4) Poulsen, W. L., U. S. Inan, and T. F. Bell, Subionospheric VLF amplitude and phase changes as a function of altitude profile of ionization in localized disturbances, *J. Geophys. Res.*, (to be submitted), March 1991.
- 5) Poulsen, W. L., U. S. Inan, and T. F. Bell, Three dimensional modeling of VLF propagation in the earth-ionosphere waveguide, *Radio Science*, (to be submitted), March 1991.

TALKS presented at Scientific Conferences

- 1) Poulsen, W. L., T. F. Bell, and U. S. Inan, 3-D modeling of subionospheric VLF propagation in the presence of localized, D-region poerturbations associated with lightning, *Fall (American Geophysical Union) meeting*, San Francisco, 1988.
- 2) Poulsen, W. L., T. F. Bell, and U. S. Inan, Three-dimensional modeling of subionospheric VLF propagation in the presence of localized D-region perturbations associated with lightning, *presented at the Ionospheric Effects Symposium conference*, Virginia, May, 1990.
- 3) Poulsen, W. L., T. F. Bell, and U. S. Inan, Subionospheric VLF signal variations due to strong D-region perturbations caused by precipitating energetic electrons, *Fall (American Geophysical Union) meeting*, San Francisco, 1990.
- 4) Bell, T. F., W. L. Poulsen, and U. S. Inan, Subionospheric VLF Signal variations due to large D-region perturbations caused by precipitating energetic electrons, *presented at the XXIII General Assembly of URSI*, Prague, September, 1990.

PhD THESIS

Poulsen, W. L., Modeling of very low frequency wave propagation and scattering within the earth-ionosphere waveguide in the presence of lower ionospheric disturbances, Electrical Engineering Department, Stanford University, 1991.